# The puzzlingly large Ca II triplet absorption in dwarf elliptical galaxies[1]

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## ABSTRACT

We present central CaT, PaT, and CaT* indices for a sample of fifteen dwarf elliptical galaxies (dEs). Twelve of these have CaT*$\sim$ 7 Å and extend the negative correlation between the CaT* index and central velocity dispersion $\sigma$, which was derived for bright ellipticals (Es), down to $20 < \sigma < 55$ km/s. For five dEs we have independent age and metallicity estimates. Four of these have CaT*$\sim$ 7 Å, much higher than expected from their low metallicities ($-1.5 <$ [Z/H] $< -0.5$). The observed anti-correlation of CaT* as a function of $\sigma$ or Z is in flagrant disagreement with theory. We discuss some of the amendments that have been proposed to bring the theoretical predictions into agreement with the observed CaT*-values of bright Es and how they can be extended to incorporate also the observed CaT*-values of dEs. Moreover, 3 dEs in our sample have CaT*$\sim$ 5 Å, as would be expected for metal-poor stellar systems. Any theory for dE evolution will have to be able to explain the co-existence of low-CaT* and high-CaT* dEs at a given mean metallicity. This could be the first direct evidence that the dE population is not homogeneous, and that different evolutionary paths led to morphologically and kinematically similar but chemically distinct objects.

*Subject headings:* galaxies: dwarf—galaxies: fundamental parameters

## 1. Introduction: the low CaT-value of high-mass galaxies

The Ca II triplet (8498, 8542, 8662 Å) is a prominent absorption-line feature in the near-infrared spectrum of cool stars. Theoretical and empirical population synthesis modelling of the Ca II triplet showed that it is a good tracer of the

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metallicity of stellar systems (Idiart *et al.* 1997; García-Vargas *et al.* 1998). This is indeed observed to be the case for Galactic globular clusters (Armandroff & Zinn 1988; Rutledge *et al.* 1997). However, in early type galaxies only a small spread of Ca II strengths was measured (Cohen 1979; Bica & Alloin 1987; Terlevich *et al.* 1990).

Recently, Cenarro *et al.* (2001) defined new line-strength indices for the strength of the Ca II triplet (CaT) and for the combined strength of the P12, P14, and P17 H Paschen lines (PaT). The Ca II index corrected for the contamination by the Paschen P13, P15, and P16 lines is denoted by CaT* (CaT*=CaT$-0.93\times$PaT). These authors compiled a large library of stellar spectra and produced fitting functions (Cenarro *et al.* 2002) that can be employed to predict index-values for single-age, single-metallicity stellar populations (SSPs) using population synthesis models (Vazdekis *et al.* 2003). These models predict that for low metallicities, CaT* should be sensitive to metallicity but virtually independent of age.

However, Saglia *et al.* (2002) (SAG) and Cenarro *et al.* (2003) (CEN) present CaT* indices for bright ellipticals and show that CaT* and central velocity dispersion $\sigma$ anticorrelate. Falcón-Barroso *et al.* (2003) (FAL) arrive at the same conclusion based on a sample of bulges of spirals. On a linear $\sigma$-scale, all samples yield essentially the same slope and zeropoint. These results provide the first evidence for an anti-correlation between a metal-line index and $\sigma$ while other metallicity indicators such as $Mg_2$ increase with $\sigma$ (Terlevich *et al.* 1990). Moreover, the CaT* values of the Es in the SAG-sample scatter around 6.9 Å, about 0.5 Å lower than expected by SSP models, given their ages and metallicities (determined independently from Lick indices). CEN do not give independent metallicities for their sample but find that the measured CaT* values, with the exception of those of a few low-mass Es, are lower than any model prediction using a Salpeter IMF.

## 2. Observations and Data Reduction

We collected long-slit spectra of 15 dEs in the Fornax Cluster and in the NGC5044, NGC5898, and Antlia Groups in the wavelength region $\lambda\lambda 7900-9300$ Å. These observations were carried out at the ESO-VLT with FORS2 during 5 observing runs in 2001 and 2002. We used the FORS2 grism GRIS_1028z+29, which, with a $0.7''$ slit, yields an instrumental broadening of $\sigma_{\rm instr} \simeq 30$ km/s. Seeing conditions were typically 0.7-1.0$''$ FWHM. Total integration times varied between 5 and 8 hours. We obtained spectra of late G to early M giant stars as velocity templates. The standard data reduction procedures were performed with ESO-MIDAS[3]. The spectra for each galaxy were bias-subtracted, flatfielded, corrected for cosmic-ray events, rebinned to a linear wavelength scale (rectifying the emission lines of the arc spectra to an accuracy of ≈1 km/s FWHM) and co-added. After sky-subtraction, the spectra were flux calibrated using spectrophotometric standard stars observed in the same instrumental setup. Since our spectral resolution is close to that of the stellar library of Cenarro *et al.* (2001) and the galactic velocity dispersions were always well below 100 km/s, no corrections for resolution effects or Doppler broadening were necessary. This was confirmed by comparing the values of the indices for the template stars in common with the library. We measured the CaT, CaT*, and PaT indices, averaged over an aperture of radius $R_e/8$ (or $1''$ for galaxies with $R_{\rm e} < 8''$), using the definitions given in Cenarro *et al.* (2001), and extracted kinematics out to 1-2 $R_{\rm e}$ (De Rijcke *et al.* 2001, 2003a).

## 3. Results

The CaT, PaT and CaT* indices of our sample dEs versus central velocity dispersion $\sigma$ are presented in Fig. 1. The majority of the dEs scatter around CaT*$\sim$ 7 Å and form the low-$\sigma$ extension of the CaT*-$\sigma$ relation of bright Es and bulges of spirals. Three out of fifteen dEs have a discrepantly low CaT*$\sim$ 5 Å value. FCC046 has CaT=8.3±0.3 Å but a very high PaT=3.3±0.2 Å, in agreement with the fact that this is an actively star-forming dE and contains a very young stellar population (De Rijcke *et al.* 2003b). FCC245 and NGC5898_dE2 (a dE in the NGC5898 group) have normal PaT values but very low CaT≈ 5.5 Å. Excluding these three galaxies, we find that CaT, PaT, and CaT* remain nearly constant over the range $\sigma = 20-55$ km/s. A detailed analysis of the

[3]ESO-MIDAS is developed and maintained by the European Southern Observatory

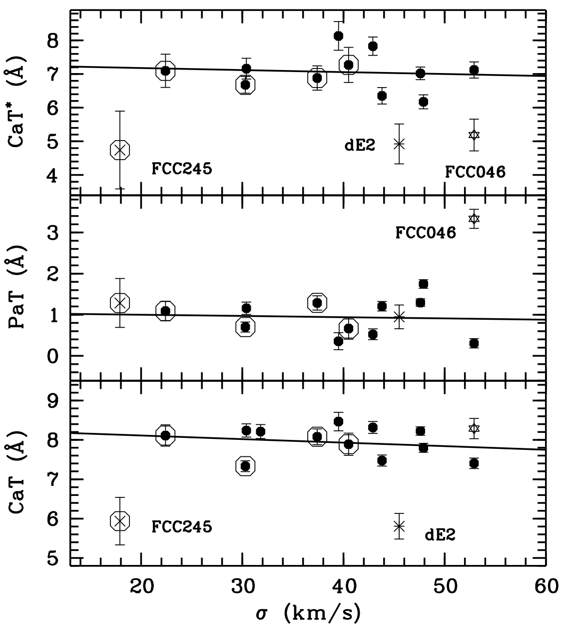


Fig. 1.— CaT, PaT and CaT* values versus central velocity dispersion $\sigma$ for our 15 dEs with a least-squares fits to the data, showing a mild anti-correlation. Three galaxies were excluded from the fit: FCC245 and NGC5898_dE2 show a very low CaT value; FCC046 has a very high PaT absorption, due to recent starformation. Galaxies appearing in Fig. 3 are marked with a circle.

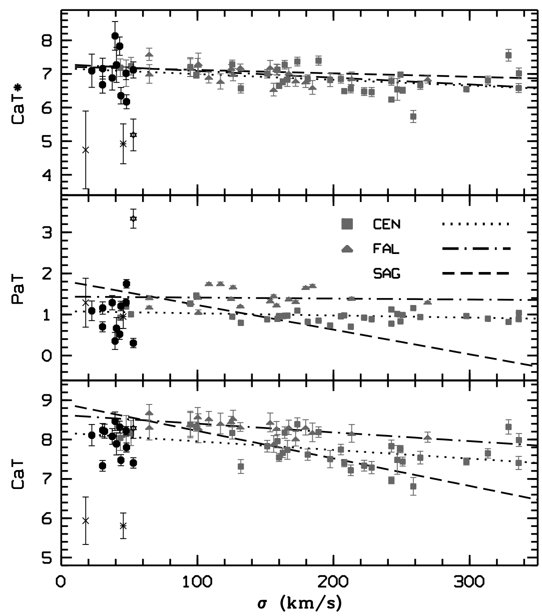


Fig. 2.— Comparison of our data with the extended relations of SAG, CEN and FAL. Data from CEN and FAL have been corrected for broadening and are shown together with linear least-squares fits to their samples and the anticorrelation found by SAG (symbols as indicated on the figure).

spatially resolved colors and line-strengths will be presented in a forthcoming paper. In Fig. 2, we present our results together with those of SAG, CEN and FAL. CEN and FAL broadened their spectra to 370 and 300 km/s respectively. In order to compare their data with ours, we used the broadening corrections given by Vazdekis *et al.* (2003) for an old population with solar metallicity and a Salpeter IMF. These corrections are model-dependent, but the maximum error introduced is $\sim 0.2$ Å. Clearly, except for the three outliers, dEs populate the low-$\sigma$ extension of the CaT*-$\sigma$ relation of bright Es and bulges. All datasets yield approximately the same slight CaT*-$\sigma$ anti-correlation. SAG find PaT to anti-correlate with $\sigma$, while the CEN data scatter around PaT$\approx 1$ Å, and FAL find PaT$\approx 1.4$ Å. The same trend is found for CaT where SAG find a stronger anti-correlation and the Es of CEN are slightly offset with respect to the bulges of FAL. These differences could be due in part to flux calibration differences and to the different ways of correcting the spectra to the system defined by the models (as discussed in FAL).

In Fig. 3, we show model predictions for CaT, PaT, and CaT* as functions of age (between 1 and 18 Gyr) and metallicity ($-1.68 <$ [Z/H] $< 0.2$). The SSP models (Salpeter IMF) are safe for all ages in the metallicity range $-0.7 \leq$ [Z/H] $\leq 0.2$, while for lower metallicities the age range 10-13 Gyr, which is of most interest to us, is safe (Vazdekis *et al.* 2003). The predicted CaT and CaT* values are strong functions of metallicity for [Z/H]$\leq -0.4$ and nicely reproduce the observed behavior of these indices in globular clusters (Armandroff & Zinn 1988), which, for all practical purposes, are genuine SSPs. However, the bright ellipticals in the SAG sample have CaT* values that are about 0.5 Å lower than expected by theory, given their ages and metallicities, signaling that some vital ingredient might be missing in the models. For 5 Fornax dEs in our sample, independently determined ages and metallicities can be found in the literature. The age and metallicity measurements of Rakos *et al.* (2001) are based on narrowband photometry employing a modified Strömgren filter system; Held & Mould (1994) use

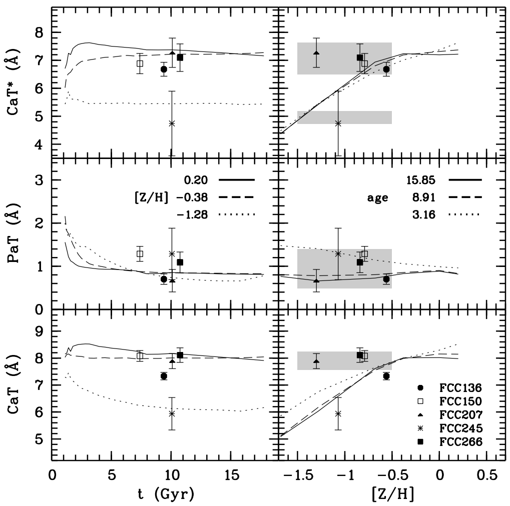


Fig. 3.— Vazdekis *et al.* (2003) SSP model predictions (Salpeter IMF) of CaT, PaT and CaT* versus age (left panel) and metallicity (right panel). The full, dashed, and dotted lines represent different metallicities and ages as indicated on the figure. The symbols show 5 Fornax dEs of our sample with independent age and metallicity estimations (Rakos *et al.* 2001; Held & Mould 1994). The shaded boxes indicate the locus of the other dEs in our sample. The metallicity range $-1.5 \leq$[Z/H]$\leq -0.5$ is taken from Rakos *et al.* (2001), while the index ranges are $1\sigma$ deviations from the mean. While the PaT values are consistent with the model predictions, the near-constancy of CaT and CaT* for our metal-poor dEs disagrees with the model predictions. Only a few dEs have low CaT*, consistent with low metallicity (lower box in CaT* panel).

age and metallicity sensitive line-strengths in the $\lambda\lambda 4000-5000$ Å region. These studies find dEs to be rather old ($\sim$ 10 Gyr) and metal-poor ($-1.5 <$ [Z/H] $< -0.5$) stellar systems. Four out of these five dEs, due to the near-constancy of CaT and CaT*, lie well above the predicted values, by up to 2 Å in the case of the most metal-poor dE. In fact, FCC245 is the only galaxy in this subsample whose indices are in agreement with its low metallicity content ([Z/H]$\approx -1.1$) and old age ($t \approx 10$ Gyr). FCC245 has a low surface brightness ($\langle\mu_{\rm e}\rangle_B = 23.5$ mag/arcsec$^2$) and its P14 line is affected by bright sky emission lines (influencing PaT and CaT* but not CaT), hence the somewhat larger errorbars. Although we do not have ages and metallicities for the 11 other dEs in our sample, one thing is clear; 9 have CaT*$\sim$ 7 Å which will place them on the same sequence as the SAG ellipticals and the 4 high-CaT* dEs presented in Fig. 3, irrespective of their ages or metallicities. The locus of these dEs in the CaT*-Z plane is indicated in Fig. 3 by the upper shaded box.

Hence, the majority of the dEs in our sample follow the same CaT (or CaT*) versus $\sigma$ or versus Z relations as bright ellipticals and bulges of spirals. The observed near-constancy of CaT and CaT* over a very wide range of metallicities ($-1.5 <$ [Z/H] $< 0.5$) is in flagrant disagreement with the prediction that these indices should be sensitive to metallicity. Three out of fifteen dEs in our sample have CaT*$\sim 5-6$ Å, in agreement with them being low-metallicity galaxies (lower shaded box in Fig. 3). This makes our observations even more puzzling; apparently, at a given metallicity, dEs with CaT*$\sim$ 5 Å and with CaT*$\sim$ 8 Å coexist.

## 4. Discussion and conclusions

In order to interpret their low CaT and CaT* in view of the current models, SAG and CEN find that model uncertainties ($\sim$ 0.5 Å) are too small to provide a solution. They consider variations of the IMF as a function of metallicity or velocity dispersion, or Ca underabundance as a possible way out.

By varying the slope of a power-law IMF, CEN change the stellar dwarf/giant ratio of the population. Since CaT* depends on the surface gravity of stars, being low in dwarf stars and high in giant stars, a high dwarf/giant ratio in the case of a high-Z SSP and a low dwarf/giant ratio in the case of a low-Z SSP, could explain both the low CaT* observed in bright Es and the high CaT* in dEs. However, there is no sound physical basis for such variations of the slope of the IMF. Theoretical derivations show that for stellar masses above 1 $M_\odot$, the IMF behaves as a Salpeter power-law and is almost insensitive to the physical conditions within star-forming molecular clouds (Padoan & Nordlund 2002). Only in the subsolar-mass regime does the environment affect the stellar mass-distribution (e.g. low ambient densities prevent the formation of very low-mass stars). In an old stellar population the contribution of subsolar-mass stars becomes more important. Using a piecewise power-law IMF with Salpeter slope for masses above 0.6 $M_\odot$ and varying slope at lower masses, SAG show that the steepening required to bring the model CaT* val-

ues in accordance with those observed in bright Es, implies higher than observed FeH 9916 Å index values (FeH is strong in dwarf stars but nearly abscent in giants) and too high stellar mass-to-light ratios (see SAG and references therein). And if the IMF would vary with Z to explain the high CaT* in dEs, why doesn't this effect manifest itself also in low-Z, low-$\sigma$ systems such as globulars?

Moreover, dEs are not composed by SSPs but can have long and complex star-formation histories (e.g. Ferrara & Tolstoy (2000)). If the IMF varies with metallicity, it will also vary in time and it remains to be seen how the use of variable IMFs in chemo-evolutionary models affects the predicted properties of dEs. Chiappini *et al.* (2000) explore a model for the Galaxy using a metallicity-dependent power-law IMF which steepens as the metallicity rises (slope $x$ =log Z+4.05), thus simulating also a temperature dependency. They find that the model predictions are in disagreement with important observational constraints and conclude that such an IMF should be rejected. Using the theoretical IMF proposed by Padoan *et al.* (1997) to investigate the formation of ellipticals, Chiosi *et al.* (1998) find that density is the leading parameter for the variations of the IMF, instead of temperature. This leads to dwarf/giant ratios that decrease with increasing galactic mass, inverse to the trend invoked by CEN. Indeed, IMFs with a low dwarf/giant ratio lead to numerous SNII explosions that rapidly recycle heavy elements into the ISM and cause $\alpha$-elements such as Mg, O and Ca to be overabundant with respect to Fe. Also, such an IMF can raise the overall metallicity to above solar.

Combining SSPs, SAG find that a rather artificial stellar mix has to be invoked (consisting of a metal-rich stellar population with a small contribution of a metal-poor one) in order to lower the predicted CaT* to the one observed in bright Es and at the same time satisfy UV constraints. Adding a (more logical) young metal-rich component to explain the observed high H$\beta$ in ellipticals only aggravates the problem, producing larger CaT* values. In dEs one could expect a small high-metallicity stellar population on top of an old low-metallicity population with the secondary star-burst triggered by e.g. gravitational interactions with giant cluster members (Moore *et al.* 1996; Conselice *et al.* 2003b). If the burst occured more than 2 Gyr ago, PaT would be essentially unaffected. We explored this scenario by adding young, high-metallicity SSPs to an old low-metallicity SSP and found that any young, metal-rich SSP must contribute more than 50% of the total mass in order to raise CaT above 7.5 Å. Then, the young metal-rich population completely dominates the light, in contradiction with the low metallicities inferred from optical linestrengths.

Another suggestion to explain the low CaT* for Es is a true Ca underabundance in giant galaxies. Although the optical Ca4227 Lick index is also reported to be weaker than model predictions (e.g. Vazdekis *et al.* (1997)), such an underabundance is hard to combine with the observed $\alpha$-element overabundance for giant Es. Also, when trying to reproduce the Ca underabundance with chemo-evolutionary models, extremely short formation timescales ($\sim 10^7$ yr), extremely flat IMFs ($x \sim 0.3$) (Mollá & García-Vargas 2000) or metallicity-dependent supernova yields (Worthey 1998) are required. On the other hand, although the sensitivity of CaT* to the Ca abundance is not yet fully understood, in this scenario the high CaT* in dEs would imply a Ca overabundance at low metallicities (see Thomas *et al.* (2003) for a detailed discussion).

To conclude, we show that 12 out of a sample of 15 dEs follow the same sequence as bright Es and bulges of spirals in CaT or CaT* versus $\sigma$ diagrams whereas 3 out of 15 have significantly lower CaT*. This could be the first direct evidence for the existence of two distinct dE populations that are morphologically and kinematically indistinguishable but have different chemical compositions. A possible explanation for this dichotomy could be that dEs evolve to their present-day state along different evolutionary paths. Two principal evolutionary sequences are galaxy harassment (Moore *et al.* 1996; Conselice *et al.* 2003a) and SN-driven galactic winds (Dekel & Silk 1986; Arimoto & Yoshii 1987), resulting in morphologically and kinematically similar stellar systems but with distinct chemical properties. The kinematics of the full sample will be presented in a forthcoming paper.

Variations of the IMF slope could explain the near-constancy of CaT* over a wide range of metallicities. However, the proposed drastic variations violate other observational constraints and

yield contradicting results when incorporated in full-fledged chemo-evolutionary models. On the whole, it is clear that we are still far from understanding the behavior of the Ca II triplet in the integrated light of stellar systems with complex star-formation histories. Only with the aid of detailed chemo-dynamical models can one hope to explore the effects of realistic IMF variations and of complex star-formation histories on the relative elemental abundances, particularly of Ca and other $\alpha$-elements, and to check how different formation scenarios reflect in the absorption-line indices of dEs.

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